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Cleavage vs. Folding vs. Thrusting: Relative Timing of Structural Events in the Central Champlain Valley

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CLEAVAGE VS. FOLDING VS. THRUSTING: RELATIVE TIMING OF STRUCTURAL EVENTS IN THE CENTRAL CHAMPLAIN VALLEY

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INTRODUCTION

The gross structure of a thrust belt (e.g. western Vermont) is controlled by the geometries of the thrust surfaces and the magnitudes of the displacements (Boyer and Elliott, 1982; Suppe, 1983). Within every thrust belt, however, there are numerous other structures that form during the same tectonic event but are not obviously related to the thrusting. It is the temporal and spatial relations between these secondary structures and the thrusting that this field trip will investigate.

Regional Setting

The structure of the central Champlain Valley has long been thought to consist of a narrow line of thrusts separating undeformed strata to the west from multiply folded strata within a recumbent synclinorium to the east (Cady, 1945). Recent mapping (Washington, 1981a, b, 1982, 1987b; Washington and Chisick, 1987; Harding and Hartz, 1987), however, has found that the area is a complex thrust belt (figure 1). In fact, the areal distribution of the strata that led to the synclinorium theory (Dana, 1877; Cady, 1945) is the result of successively older strata being brought to the surface by the thrusts east of the "axis of the synclinorium."

The Western Vermont thrust belt consists of four major thrust systems: the carbonate thrust sheets (herein called the Middlebury thrust system) at the base, the Champlain thrust sheet above, the New Haven-Green Mountain (NH-GM) thrust system overriding the trailing edge of both of these, and the Taconic allochthons to the south sitting atop the Middlebury and NH-GM systems. As Keith (1932) recognized, each of these thrust systems has a distinct stratigraphy. Recent work is redefining the correlations among the sequences (Washington and Chisick, 1987). Figure 2 summarizes the stratigraphy of the thrust belt and compares it with the autochthonous strata along the edges of the Adirondacks. This field trip will concentrate on the

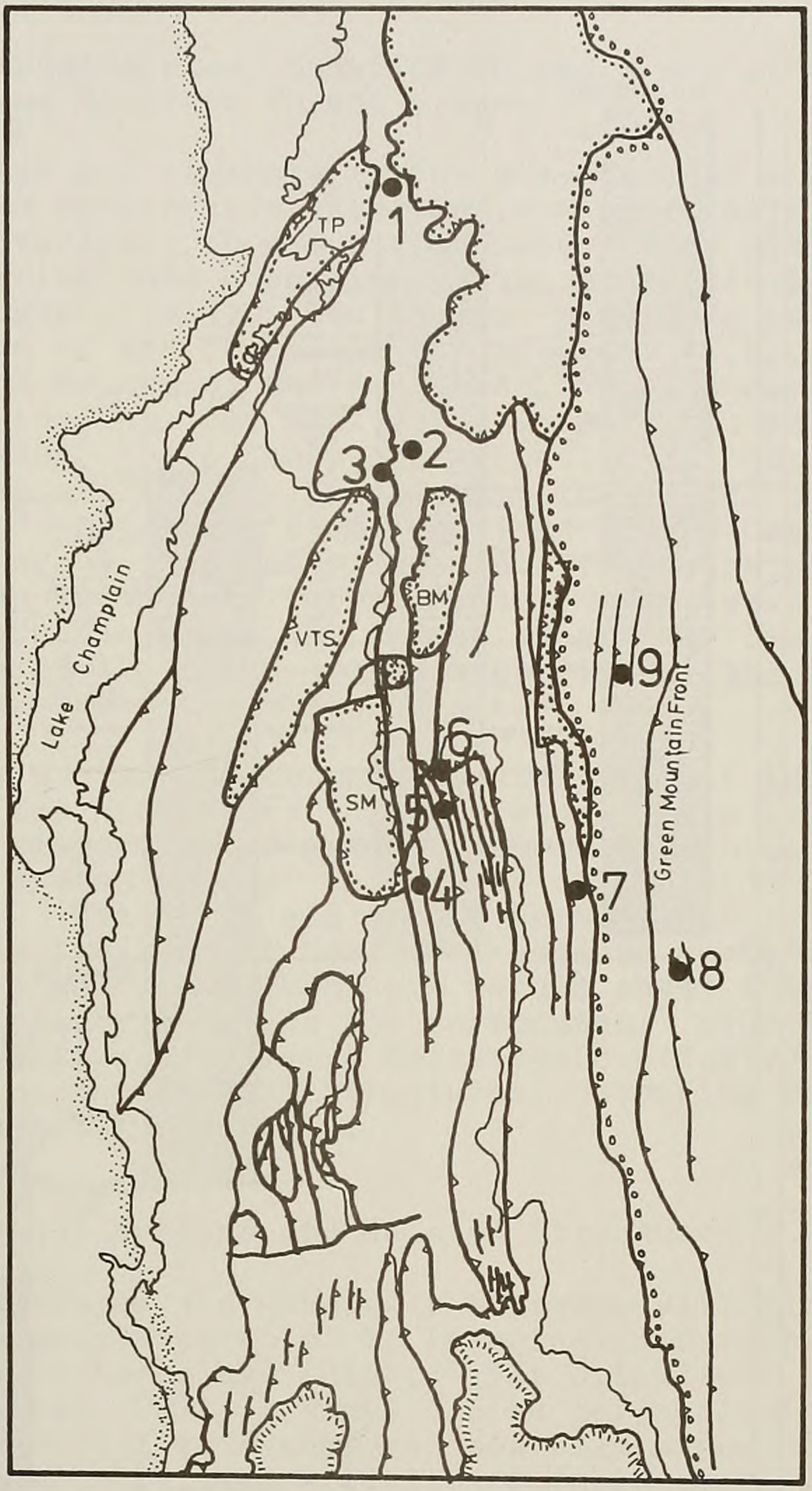

Figure 1 - Structure map of the central Champlain Valley. Autochthon extends west from fine stipple, New Haven - Green Mountain thrust system extends east from line of open circles, north end of Taconic allochthons are denoted by hatchures, and edges of Champlain thrust sheet (including isolated pieces) are marked by heavy dots; intervening area is the Middlebury thrust system. TP - Thompson's Point; VTS - Vergennes thrust sheet; BM - Buck Mountain; SM - Snake Mountain; field trip stops indicated by numbers.

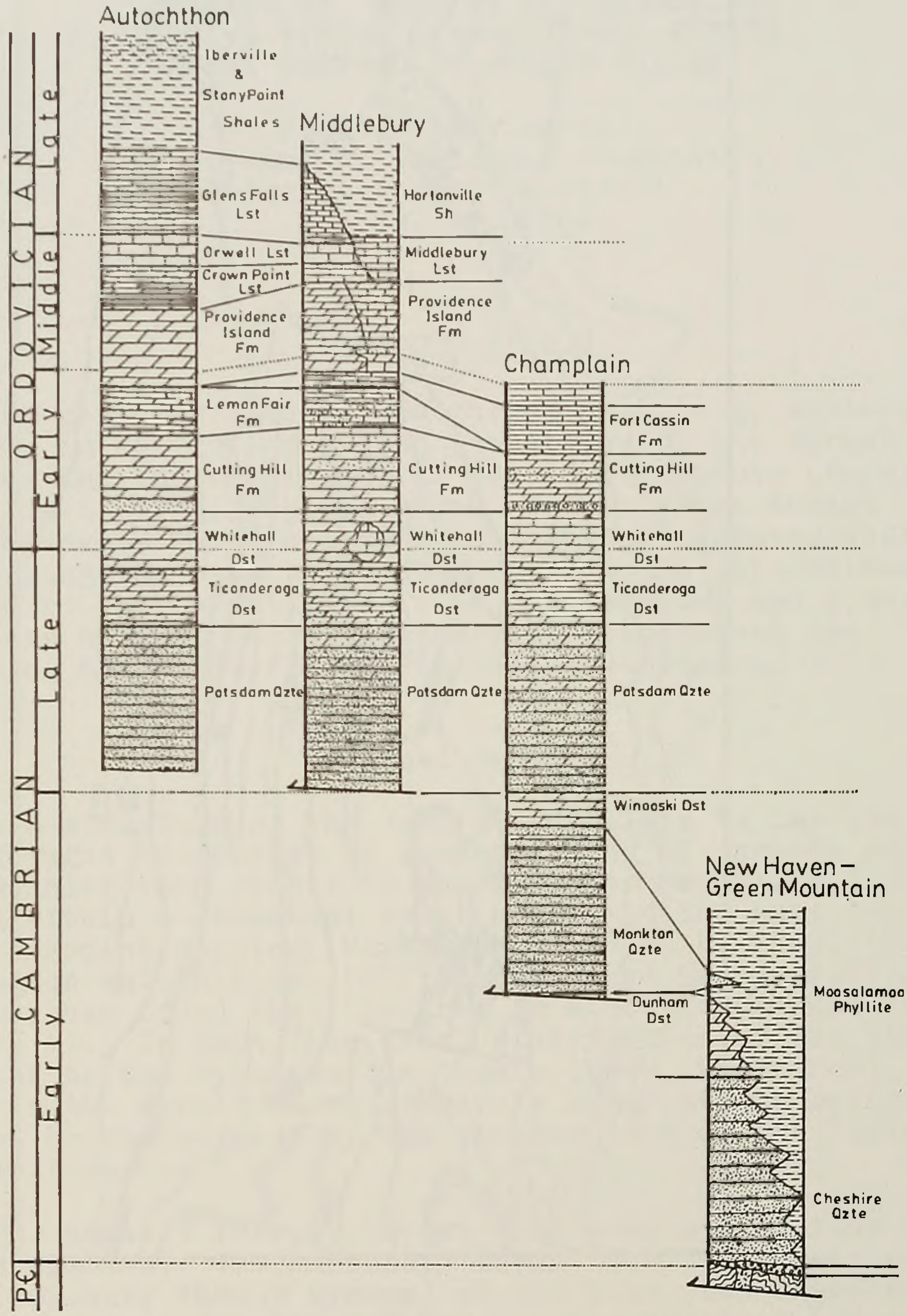

Figure 2 - Comparison and correlation of the stratigraphic packages encountered in the autochthon and the Middlebury, Champlain, and New Haven - Green Mountain thrust systems in the central Champlain Valley.

Middlebury thrust system, but STOPS 8 and 9 are within the New Haven-Green Mountain thrust system.

One of the key elements in the structure of this thrust belt is penetration thrusting. A penetration thrust breaches an overlying thrust surface and places structurally lower material onto a portion of the structurally higher sheet (Washington, 1985). The present positions of the western pieces of the Champlain thrust sheet (i.e. Snake Mountain, Buck Mountain, the Vergennes thrust sheet, and Thompson's Point) has led most prior workers (Logan, 1860; Dana, 1877; Cady, 1945; Coney and others, 1972) to infer that the Champlain thrust lies beneath the "Middlebury synclinorium." Actually, these portions of the Champlain thrust sheet are tectonically isolated by penetrating thrusts of the Middlebury thrust system. This will be seen at STOP 4 where the Weybridge thrust sheet overlies the trailing edge of the Snake Mountain portion of the structurally higher Champlain thrust sheet.

There is a high metamorphic gradient within the eastern parts of the Middlebury thrust system. This is produced by the juxtapositon of greenschist metamorphics of the NH-GM thrust system against carbonates of the Middlebury thrust system. The north end of the Vermont marble belt lies about the latitude of New Haven because north of there the trailing edge of the Champlain thrust sheet intervenes between the metamorphics and the carbonates. STOP 7 is the Middlebury marble quarry where metamorphic effects are superimposed on thrust-belt structures, obscuring the detailed structural relations.

Thrust Systems and Related Structures

Thrust surfaces are generally stepped, with alternating flats (segments parallel to layering) and ramps (segments oblique to layering) (Rich, 1934; Dahlstrom, 1970; Boyer and Elliott, 1982). Ramps can be perpendicular, oblique, or parallel to transport (see Wilson and Stearns, 1958, Dahlstrom, 1970, and Elliott and Johnson, 1980). Displacement over the steps produces "fault-bend" folds (Suppe, 1983) which are generally large, flat-topped, and asymmetric. At STOP 1 we will see some nice examples of such folds in small thrust systems.

There are two basic types of thrust systems - duplexes and imbricate fans (Boyer and Elliott, 1982). Duplexes are thrust systems in which the various thrusts branch off of a common basal (floor) thrust and join a common overlying (roof) thrust. Imbricate fans, on the other hand, are thrust systems in which the various thrusts branch off of a common basal thrust and climb up through the overlying strata until they either reach the surface or go blind (end without connecting to the surface or another thrust). The Champlain thrust system is an emergent imbricate fan; the structurally lower Middlebury thrust system, however, is a duplex for which the Champlain thrust (and Taconic thrust to the south) was the roof. The tectonic dismembering of the Champlain thrust sheet occurred when imbricate thrusts of the Middlebury system breached the Champlain thrust rather than joining it.

Generally, fault-bend folds are the last major structural element to develop in a thrust sheet unless there are multiple tectonic events or out-of-sequence deformation (Coward, 1984). Because thrusting progresses downward and forelandward, deformation in lower (later) thrust sheets can affect higher (earlier) thrust sheets (Elliott and Johnson, 1980; Mitra and Yonkee, 1985). Where the lower thrust sheets are exposed, however, the source of this deformation is usually clear. The only other type of deformation that does not pre-date fault-bend folding is "ramp-bend" folding which will be discussed below.

Adjacent to thrust surfaces there are commonly zones of higher deformation. In brittle rocks these zones are marked by cataclasis, whereas in ductile rocks they are generally marked by drag folding and cleavage. The deformation within these zones diminishes in intensity with distance from the fault surface. Examples of this deformation will be seen at STOPS 4 and 5. Some thrusts do not develop noticeable zones of deformation, however, all of the displacement apparently being confined to the fault surface (e.g. STOP 2). Where conditions are just right, secondary thrust systems can form immediately below major thrusts. If the major thrust causes a great increase in overburden, cleavage can form within the secondary thrust systems after fault-bend folding (e.g. STOP 1).

Secondary Structures

There are three structures which are generally associated with thrusting: folds, cleavage, and joints. All of these record shortening of the material; the direction of shortening is roughly perpendicular to the fold axes and cleavage planes and perpendicular and parallel to the two orthogonal joint sets. Where these structures are penetrative (i.e. developed throughout a thrust sheet) they form prior to thrust displacement (Washington, 1987a); only localized structures form during displacement. Regional joints are most evident in competent strata, whereas folds and/or cleavage are dominant in ductile strata. In the Champlain Valley, most of the strata fall within the ductile range, so cleavage and folds are common.

As Henderson and others (1986) recently pointed out, the relative timing of cleavage and fold development is a function of the material properties. Since folding is strongly controlled by layer thickness and layer-boundary strength (Kuenen and de Sitter, 1938; Ramsay, 1967) while cleavage formation is primarily controlled by ductility and stress magnitude (Hobbs and others, 1976), folds will develop first if the material is thinly bedded and stiff and cleavage will develop first if the material is massive and ductile. Cleavage and folds can be coeval if conditions are intermediate between these two extremes.

Where cleavage forms first, subsequent folding will reorient the cleavage, creating a cleavage fan (Fisher and Coward, 1982). Where folds form first, cleavage orientation is consistent throughout (Henderson and others, 1986). The relative orientations of the fold axial surfaces and the cleavage planes indicates the relative orientations of the stress field during the formation of the two structural elements.

Although folds can only form where there has been some shortening parallel to layering, cleavage can form even where shortening is nearly perpendicular to layering. The orientation of cleavage is a good indicator of the environment in which it formed. Cleavages that are nearly perpendicular to layering (e.g. STOPS 2 and 8) are generally formed directly ahead of a step in an active thrust. Cleavages that are nearly parallel to layering (e.g. s_1 at STOP 5), on the other hand, are generally formed beneath a thick thrust sheet advancing across a flat; the increased load causes the shortening and the taper toward the foreland causes the deviation from horizontal.

The morphology of the cleavage is primarily a function of material properties (Hobbs and others, 1976; Cosgrove, 1976; Engelder and Geiser, 1979): a fine-grained rock will form a slaty cleavage (especially if it is monomineralic), an impure sandstone or limestone will form a spaced cleavage, and a strongly anisotropic rock will tend to form a crenulation cleavage (unless the stress is applied in the wrong orientation). Thus, in the Champlain Valley the shales and pure micritic limestones exhibit slaty cleavage (STOPS 1, 4, 5, 6, and 9), the impure limestones and sandstones contain spaced cleavage (STOPS 2, 3, 4, and 8), and second generation cleavages in the limestones and slates are crenulation cleavages (STOPS 5 and 6).

Ramp-Bend Fold Trains

Although folds and cleavage generally form prior to thrust displacement, small areas contain trains of late folds, often accompanied by cleavage. These anomalous areas always occur at the junction between two differently oriented fault-bend folds. The folds are generally oriented somewhat oblique to regional strike and plunge rather noticeably toward the more hindeward end. Due to their peculiar location and timing, these fold trains are attributed to the room problems above ramp intersections during the fault-bend folding process; thus the term "ramp-bend fold trains" is applied. STOP 6 is an excellent example of a ramp-bend fold train.

Fault-bend folds form above hangingwall ramps as they advance up stepped thrust surfaces from their original seats (Suppe, 1983). The orientation of the hangingwall ramp has little bearing on the shape of the fault-bend fold since the shape is dictated by the necessity to maintain surface length and volume in the thrust sheet while it remains in continuous contact with the underlying fault surface. When two differently oriented ramps meet, the folding process becomes more complex; the theoretical fault-bend fold shape is not possible within the zone of overlap because it would necessitate drastically decreasing the surface area. Since the fault-bend folds must be accomodated, however, an effective reduction in surface area must occur. This is accomplished by shortening the layers with short-wavelength folds (fig. 3), often with accompaning cleavage.

The amount of shortening varies within the overlap zone, the greatest occuring in the central portion decreasing to zero towards the edges, especially the edge toward the more frontal ramp. Where the ramp-bend is created by the junction of a frontal and an oblique (or lateral) ramp, the shortening commonly extends along the oblique ramp farther than might be expected, making quantification of the strain produced by various ramp-bend geometries of limited

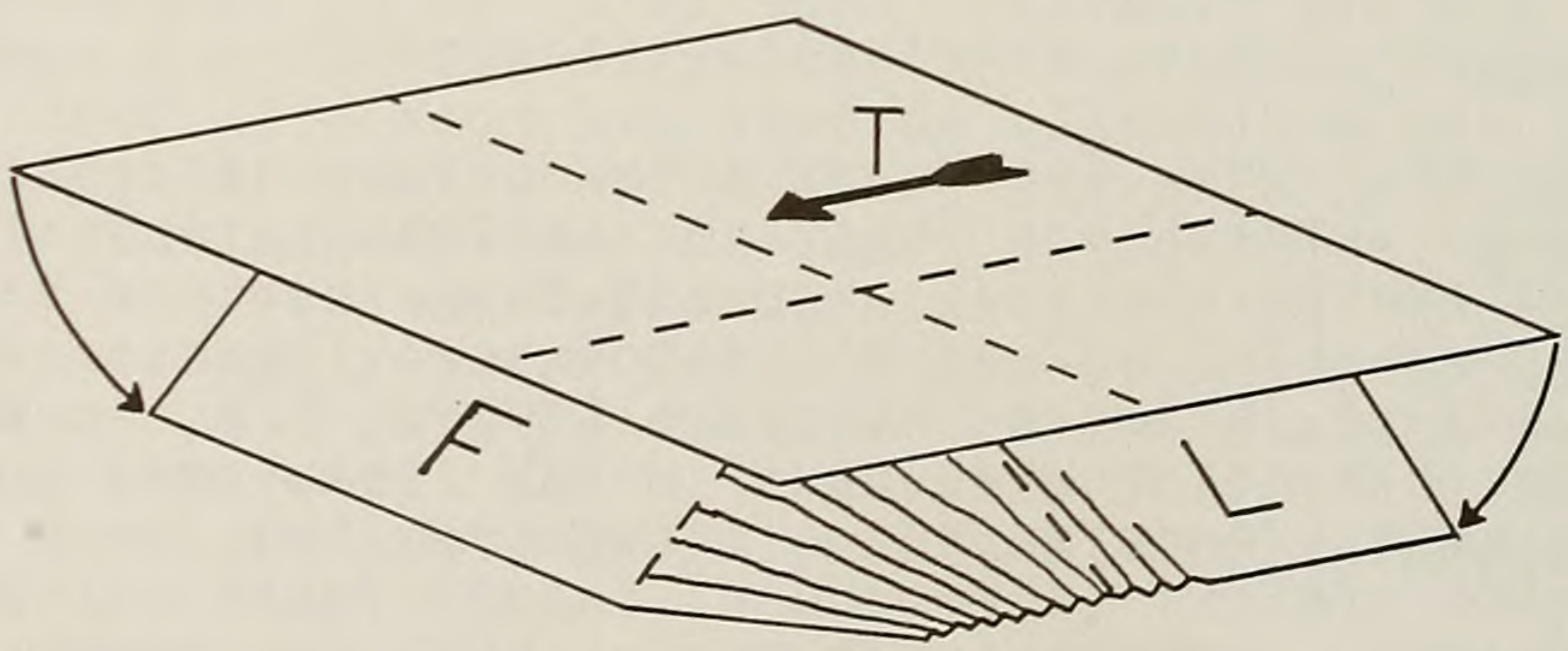

Figure 3 - Ramp-bend folds accomodate surface area decrease in zone of overlap between frontal (F) and lateral (L) fault-bend folds. T indicates transport direction.

use. This hindeward extension of the fold trains is probably due to drag along the tapered edges of the sheets.

Although there are many different possible fold patterns that could accomodate the diminution of the surface area within the overlap, the folds always have a trend between that of the two fault-bend folds. This consistency of orientation is not surprising, however; the stress field in an active thrust sheet would force the folds to be oriented tangential to the edge of the thrust sheet. The slight rotation of the folds toward the orientation of the more hindeward ramp can be attributed to the aforementioned drag on the tapered edge.

Discussion

From the preceding review of thrust belt structures, it is obvious that the relative timing of structural elements in a thrust belt is not constant. Rather, the relative timing is determined by material properties and the tectonic environment. To further complicate the picture, each thrust sheet should be considered separately since the tectonic history of each is slightly different.

Fortunately, there are many clues to the origins of the various structural elements. The orientation of a cleavage and its relation to accompanying folds gives some indication of the orientation and history of the stress field and the character of the material. The areal distribution of these elements provide further clues to the gross structure of the thrust belt.

In the Champlain Valley there are several sets of cleavage and folds (although prior workers [e.g. Crosby, 1963; Voight, 1965, 1972; Coney and others, 1972] have tended to lump them together). Generally the folds accompany cleavages formed prior to the cleavage, indicating that layer thickness and boundary strength were sufficiently low. By using the distribution of these elements, thrusts can be identified even when they are not exposed and detailed structural relations can be deciphered. Thus, the secondary structures are providing valuable insights into the structural development of western Vermont.

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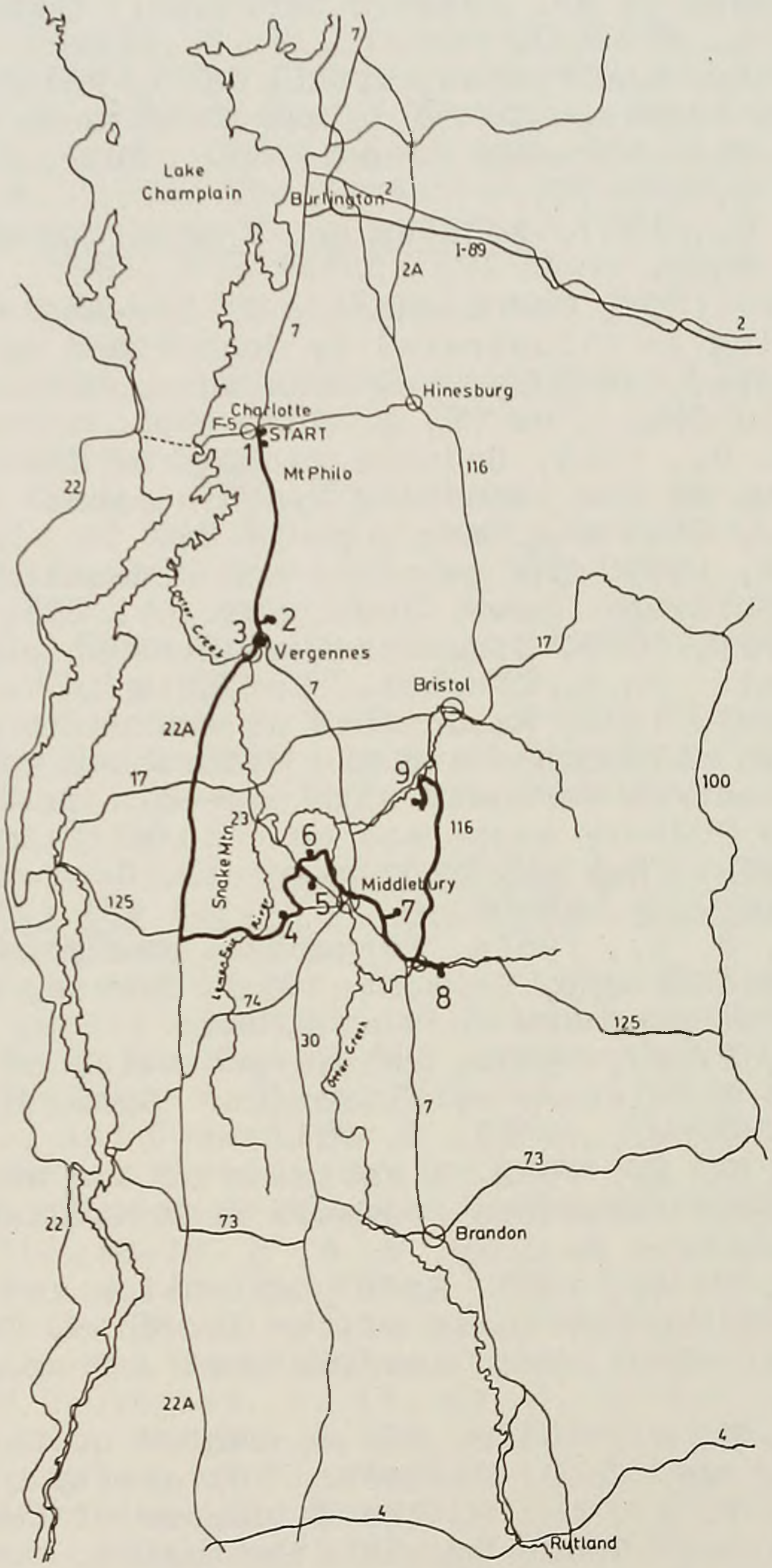

Figure 4 - Route of field trip in western Vermont.

ITINERARY

Assembly point is the gas station (currently BP) at the intersection of Routes 7 and F-5 in Charlotte. Time: 9:00 A.M.

Mileage

0.0 Go south on Route 7.

0.4 STOP 1: Charlotte Roadcuts. These roadcuts provide an excellent view of thrust structures developed in the shales directly beneath the Champlain thrust (Champlain thrust lies near top of hill). Thrust surfaces, fault-bend folds, and slaty cleavage can be seen in this roadcut. Note that the cleavage post-dates thrusting and fault-bend folding. The orientation of this cleavage indicates it formed in response to the imposition of a large overburden, probably the Champlain thrust sheet after it overrode these shales. The thrusts developed during movement on the Champlain thrust. This is the south end of Stanley's (1969) stop 5.

Continue south on Route 7.

2.1 Hill to left is Mount Philo. Cliffs near top are Monkton quartzite of the Champlain thrust sheet. Thrust lies about at base of cliffs.

9.0 Turn left onto Satterly Road.

9.2 STOP 2: Hammond Quarry. North face of this quarry contains a small thrust in Glens Falls limestone. Note the strong spaced cleavage and detachment surfaces in the footwall. The cleavage and detachments are basically coeval. Both formed in resonse to horizontal tectonic compression during active movement on the overlying thrust (Washington, 1987).

Turn around and proceed back to Route 7.

9.4 Turn left and continue south on route 7.

9.9 Turn right onto Route 22-A. Stop as soon as you are clear of the corner.

10.0 STOP 3: Vergennes Roadcut. The low roadcut along the south side of Route 22-A has well developed folds and cleavage. The cleavage is clearly unaffected by the folds, indicating that it formed later. The cleavage is parallel to the axial planes of the folds, however, so the structures are probably penecontemporaneous.

Continue south on Route 22-A.

11.4 The Vergennes falls are the last falls on Otter Creek. The falls consist of Whitehall dolostone of the Vergennes thrust sheet (a tectonically isolated piece of the Champlain thrust sheet) with the thrust plane reaching the surface about the base of the falls. Otter Creek is navigable from here to Lake Champlain, so this is where Commodore Macdonough built his fleet that defeated the British fleet at the Battle of Plattsburgh in 1814. At the end of Otter Creek is the site of Fort Cassin (built to protect the fleet during construction), the type locality of the Cassinian stage (Early Ordovician).

For the next few miles Route 22-A follows the ridge formed by the Vergennes thrust sheet. The low outcrops along the road are Whitehall and Ticonderoga dolostone. The broad valley to the west is underlain by Late Ordovician shales.

16.8 Ahead and to the left is Snake Mountain, the first American locality to be recognized as having non-sequential stratigraphic stacking. The occurrence of the Early Cambrian Monkton quartzite atop Late Ordovician limestones and shales caused considerable controversy (see Emmons, 1842, and Adams, 1848) which was resolved only when Logan (1860) defined the Logan's line thrusts with this as the type locality. The Champlain thrust lies about at the base of the upper cliffs, which are Monkton quartzite.

24.8 Turn left onto Route 125.

27.8 The south end of Snake Mountain. This is the south end of the Champlain thrust as mapped by Cady (1945) and recorded on the state geologic map. All strata for the next 10 km south are of Ordovician age.

28.4 Lemon Fair River.

29.5 The cliffs that face you are the hangingwall of the Weybridge thrust, a penetration thrust which places Ordovician strata over the lower Cambrian strata of the Snake Mountain portion of the Champlain thrust sheet. Unfortunately, the thrust surface is not exposed.

30.4 STOP 4: The Ledges. These ledges provide one of the best exposures of the upper Beekmantown Group in the Group in the Champlain Valley. The limestones at the base are Lemon Fair formation (this is the type locality) and uppermost Cutting Hill formation. The shaly strata are Fort Cassin formation and the overlying limestones and dolostones are Providence Island formation. The Providence Island strata are highly deformed, whereas the underlying strata are basically undeformed; the floor thrust of the Sudbury duplex lies just above the base of the Providence Island formation. Note the decrease in cleavage intensity with distance below the Sudbury floor thrust (a true detachment). There is also some drag folding immediately below the detachment surface.

Continue uphill on Route 125.

31.0 Turn left onto Samson Road.

32.2 Bear right onto dirt road. The ledges to the north and south of this intersection contain folded and faulted Lemon Fair strata. The folds and faults are part of a ramp-bend fold train associated with a lateral ramp along the Weybridge thrust.

32.7 Lateral cutoff of the top of the Lemon Fair formation lies to left.

32.9 Lunch. Bittersweet Falls. The falls consist of Middlebury limestone, the contact with the overlying Hortonville slate occurring just above the top of the falls. Extending east from the top of the falls is a winding canyon providing a continuous exposure through the slate that forms the "core of the Middlebury synclinorium." The eastern boundary of the slate is a thrust fault (one of the imbricates of the Sudbury duplex) and several other small thrusts can be seen within the slate. Two generations of cleavage can be identified locally in the slate:
1) a nearly bedding-parallel cleavage (axial planar to folds near the top of the section) and
2) a crenulation cleavage. The former formed in response to the superposition of the Champlain thrust sheet (which formed drag folds in the upper strata). The latter formed in response to shear strains near thrusts formed during duplexing. The limestones at the falls only show the former of these cleavages.

After lunch continue north on road.

33.5 Turn left.

33.7 Turn right onto Route 23 (paved road). The monument at corner is to Silas Wright, a Governor of New York who came from this town (Weybridge).

34.6 STOP 5: Dubois Quarries. There are two small limestone quarries to be visited here, one on the northwest side of the barn and the other about 150 meters west on the south end of a hillock. The first of these is an excellent exposure of the relations between bedding and two cleavages. As with most of the strata in the duplex, these limestones are basically unfolded. The earlier cleavage cuts across bedding at a very low angle, dipping slightly to the east. The second cleavage is a crenulation cleavage which deforms the first cleavage planes. The floor of this quarry is essentially the surface of one of the larger displacement imbricate thrusts in the duplex. The exposed strata are the basal portion of the Middlebury limestone. Crenulation cleavage forms in lower part of the thrust sheet (here through the entire quarry) in response to the shear along the fault plane.

The other quarry contains upper Middlebury limestone with a small shear zone along the top (top of quarry face is approximately top of shear zone). This shear zone is also marked by crenulation cleavage. Whether this shear zone represents a thrust is not clear.

These quarries were opened to provide stone for the bridge in the center of Middlebury. Stone from the first quarry can be seen in the bridge abutments above street level. The quarries were abandoned prematurely after a boiler on a quarry machine exploded under one of the workers.

Turn around and proceed back northwest on Route 23.

35.5 Turn right onto Hamilton Road (dirt).

36.0 STOP 6: James Pasture. The pasture to the north of this road is one of the classic structure localities in the Middlebury area (see Crosby, 1963, and Coney and others, 1972). It contains an easily mapped fold train with an axial-plane cleavage. There is also a later crenulation cleavage. The south and west sides of this knoll coincide with the Sudbury thrust (the eastern part of the roof thrust of the duplex. The folds seen here are part of a ramp-bend fold train formed by the intersection of the frontal and lateral ramp of the Sudbury thrust along the northern edge of the duplex (the Sudbury nappe marks the southern end of the duplex). Note the southeasterly plunge of the fold axes. These folds die out a short distance to the north. The boundary between the Middlebury limestone and Providence Island formation is marked by a thin shale layer, the marker bed used by Crosby (1963) to define the fold train.

Continue east on Hamilton Road.

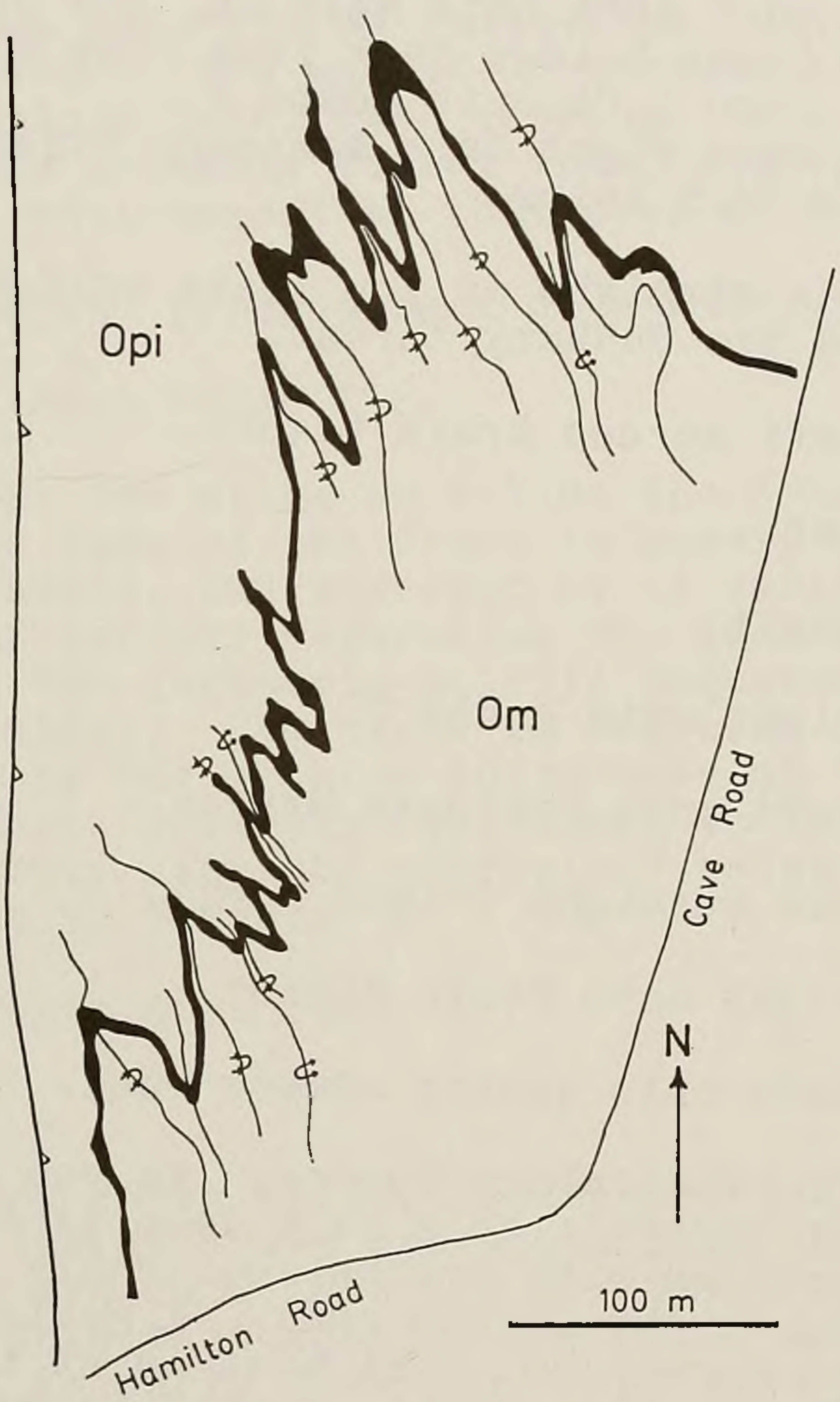

Figure 5 - Structure of James Pasture (after Crosby, 1963). The marker bed is a thin (.5 m) shale layer separating the Middlebury limestone (Om) from the dolostones and limestone of the Providence Island formation (Opi). Note the orientation of the folds relative to regional strike which is nearly due north.

36.9 Turn right.

37.5 UVM Morgan Horse Farm.

38.7 Bear left. Pulp Mill Covered Bridge - oldest covered bridge in Vermont and one of very few two lane covered bridges still in existence. If your vehicle is too large to go through:

- 0.0 turn right and continue southwest to Route 23
- 0.4 turn left onto Route 23 and go to end
- 1.2 turn left go to intersection
- 1.3 turn left onto Main St. and proceed to Route 7 (note bridge rock from Stop 5)
- 1.5 turn left onto Route 7
- 1.6 turn right onto Seminary Street (by church). = 39.8 below.

38.8 Continue straight as you leave bridge. You have just crossed the Sudbury thrust.

39.5 Turn left across train tracks.

39.5 Turn left.

39.6 Turn Right.

39.7 Turn right onto Route 7.

39.8 Turn left onto Seminary Street.

40.1 Continue straight (right fork).

41.1 Bear right onto Foote Street.

42.1 Turn left onto quarry access road.

42.3 STOP 7: Middlebury Quarry. As you enter the quarry, be very careful; this is a deep quarry and is still in operation with trucks constantly entering and leaving on the access road. A geologist of the Vermont Marble Co. will meet us at this stop.

The marble of this quarry is cut by several thrusts which have been obscured by later recrystallization during metamorphism. The original layering can be recognized by interspersed pelitic layers which also show later cleavages. The stratigraphic position of the marble is not established, but I assign it to the Lemon Fair formation based on structural position relative to nearby fossil localities.

Leave quarry.

42.5 Turn left as you leave access road.

43.4 Turn left onto Route 7.

44.7 Turn left onto Route 125.

46.3 Narrow bridge with dangerous curve.

46.5 STOP 8: East Middlebury Roadcut. Park to left of road in small parking area. The roadcut on south side of road shows a rotated early spaced cleavage. The rotation occurred as fault-bend folds formed during movement on a series of thrusts along the base of the mountain front (see Harding, this volume). The cleavage probably formed in an equivalent structural environment to that seen at Stop 2.

Turn around and proceed back down hill.

47.8 Turn right onto Route 116.

For the next few miles we follow the Green Mountain front. The base of the front is mostly hidden by glacial gravels, but wherever it is visible there is a series of thrusts separating the quartzites of the front from the carbonate-pelitic sequence of the adjacent valley. The hills to the west of the road are caused by the massive dolostones at the base of this sequence (probably equivalent to the dolostone lying directly atop the quartzite) being brought to the surface by thrusts.

56.6 Turn left onto dirt road.

57.6 Turn left.

58.0 STOP 9. New Haven Mills. Southwest facing ledges just into behind house provide a nice view of a fold and thrust system within the New Haven metamorphic complex. Note that most of the folds are related to thrusting. An early cleavage, seen best in the purer dolostones, pre-dates these folds.

Beware of the poison ivy growing along edge of woods.

End of trip.
To return to route 116, turn around, proceed back down road to end (across bridge), turn right, and go 0.8 mi.

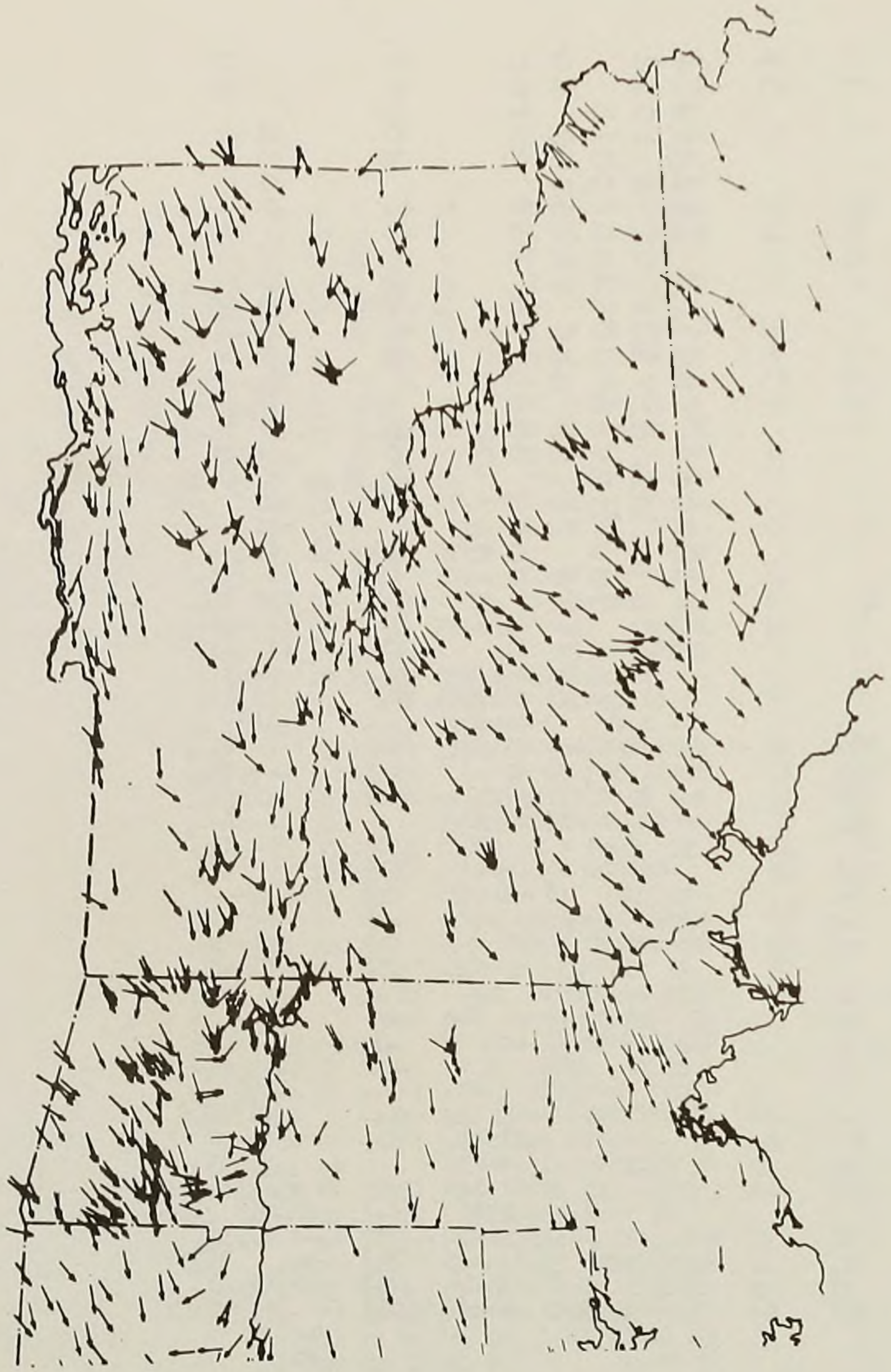

Figure 1. Compilation of striations in Vermont and New Hampshire by James W. Goldthwait (portion of Fig. 5-3 in Flint, 1957, p.60).

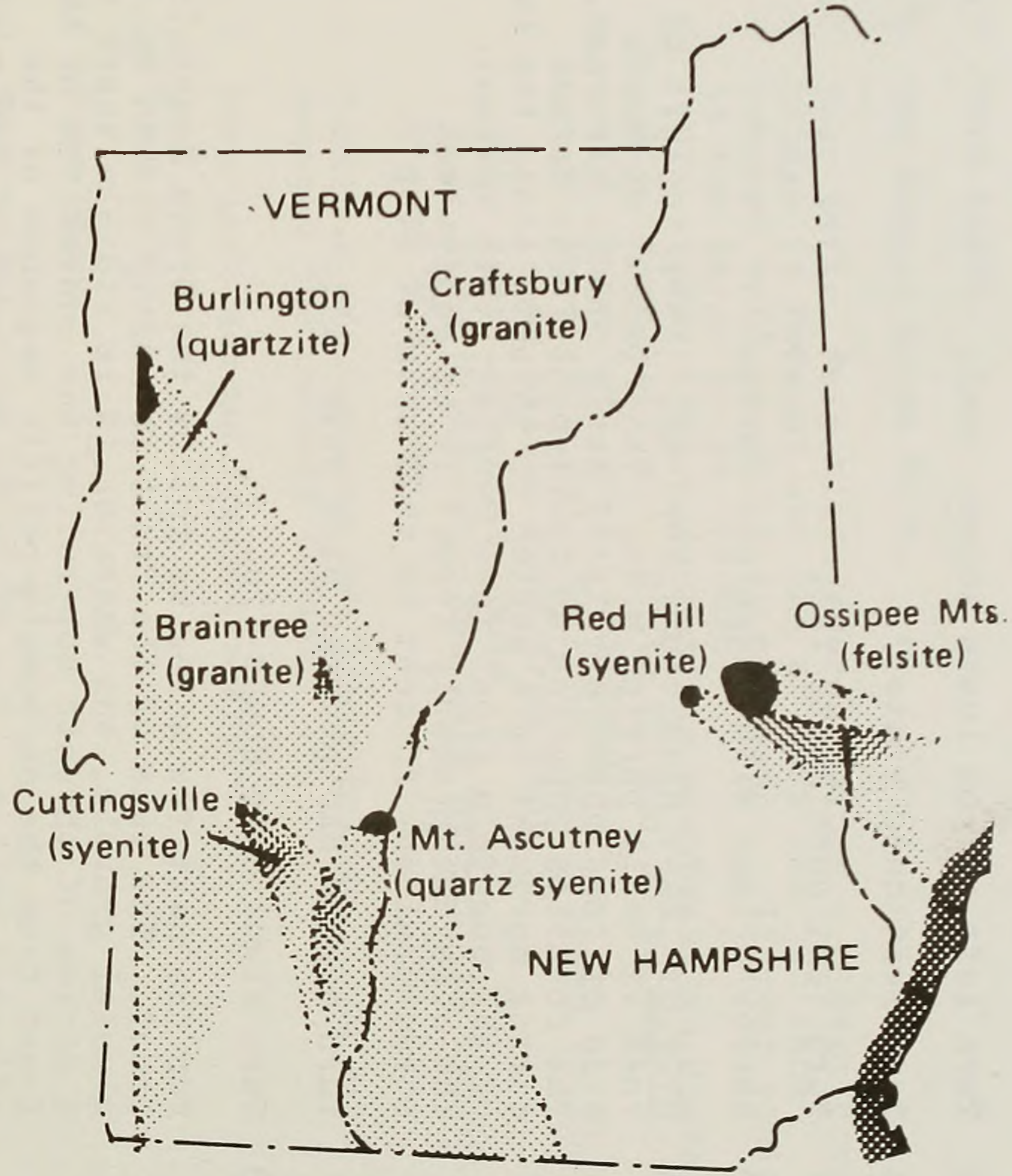

Figure 2. Indicator fans in Vermont and New Hampshire (portion of Fig. 7-19 in Flint, 1971, p.178).